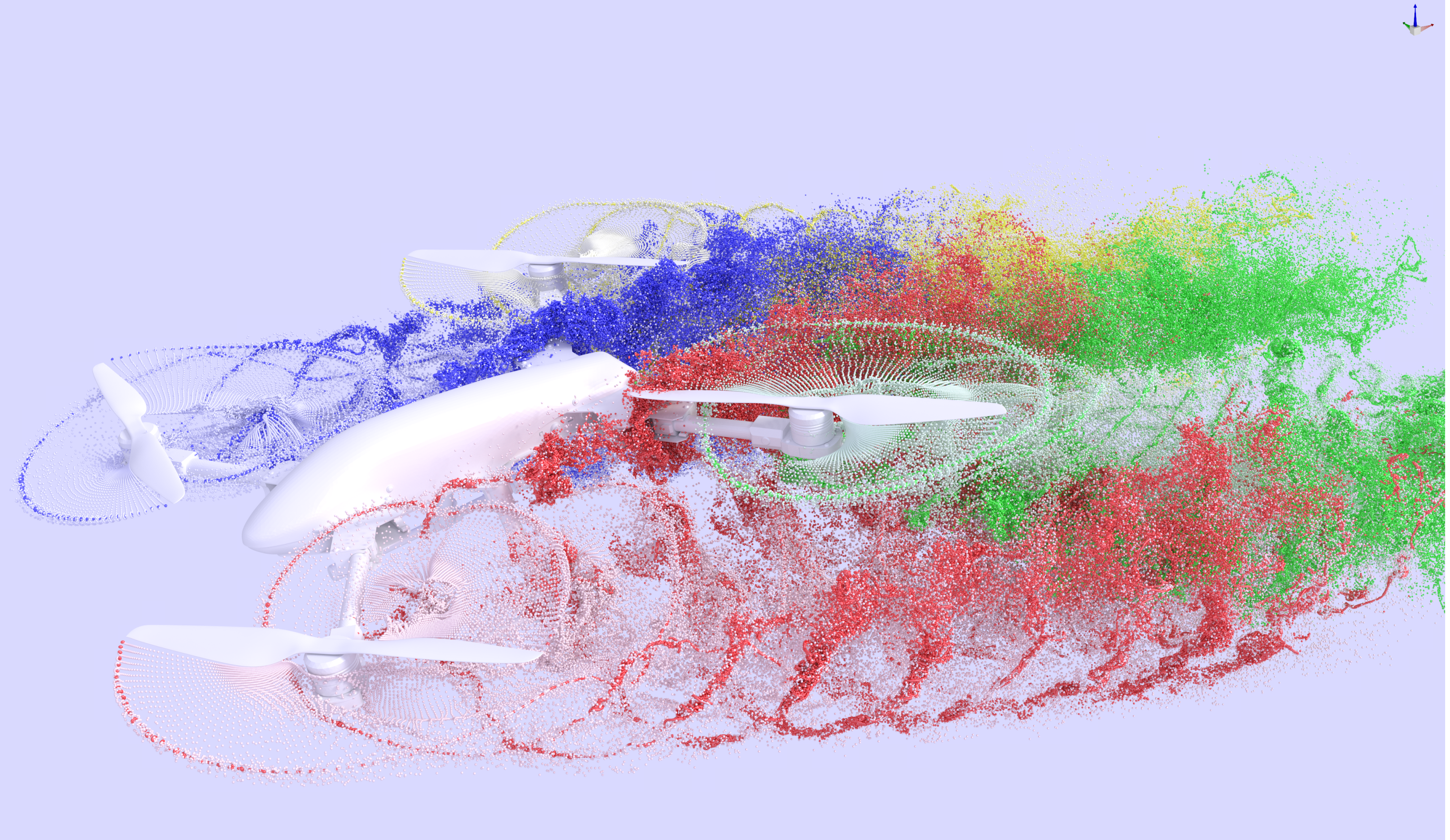


Predicting Quadcopter Drone Noise Using the Lattice Boltzmann Method

Francois Cadieux, Michael Barad, James Jensen, and Cetin Kiris

Computational Aerosciences Branch

NASA Ames Research Center

Supercomputing 2019

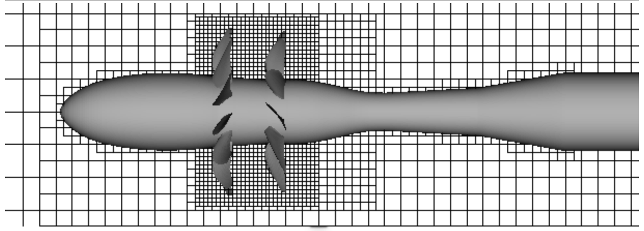
Motivation

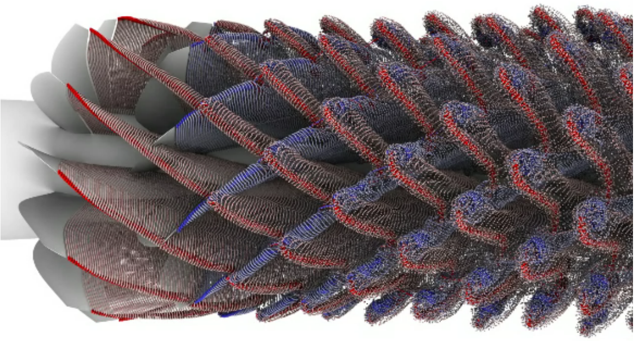
- Community noise is a major concern for drone delivery of packages and for urban air mobility vehicles (air taxis)
- Rotor tonal noise is fairly well-understood and can be predicted accurately with simple tools
- Multi-rotor interaction and rotor-fuselage interaction is harder, but still within the realm of possibility
- Reliable and accurate predictions of broadband noise of a full multi-rotor vehicle have yet to be demonstrated

Picture credit: *NASA / Lillian Gipson*

CFD Grid Paradigms

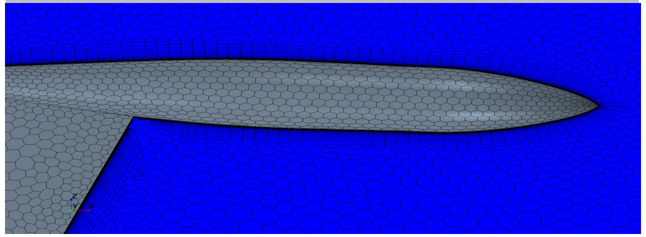
Structured Cartesian AMR

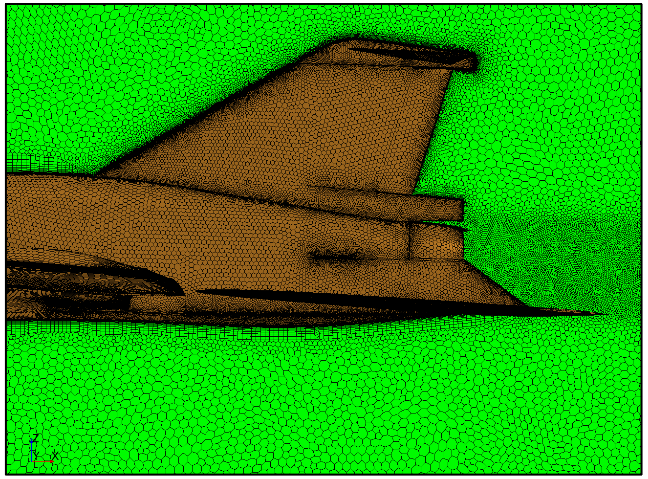




- Essentially no manual grid generation
- Highly efficient structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

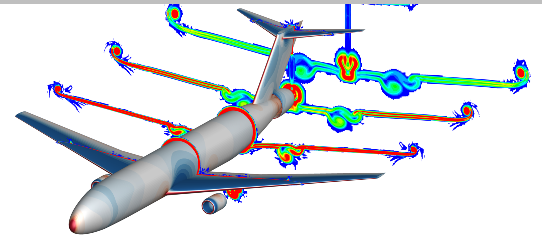
Unstructured Arbitrary Polyhedral

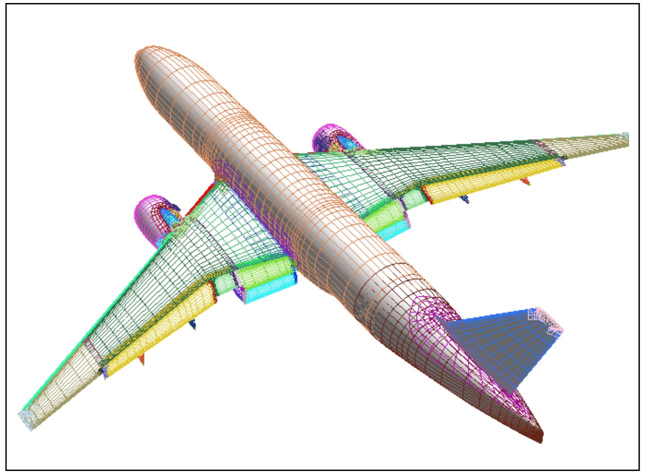




- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

Structured Curvilinear

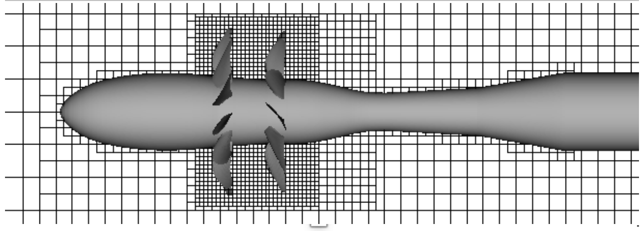


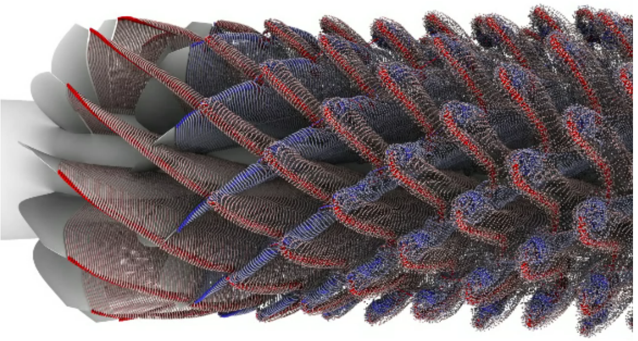


- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

CFD Grid Paradigms

Structured Cartesian AMR



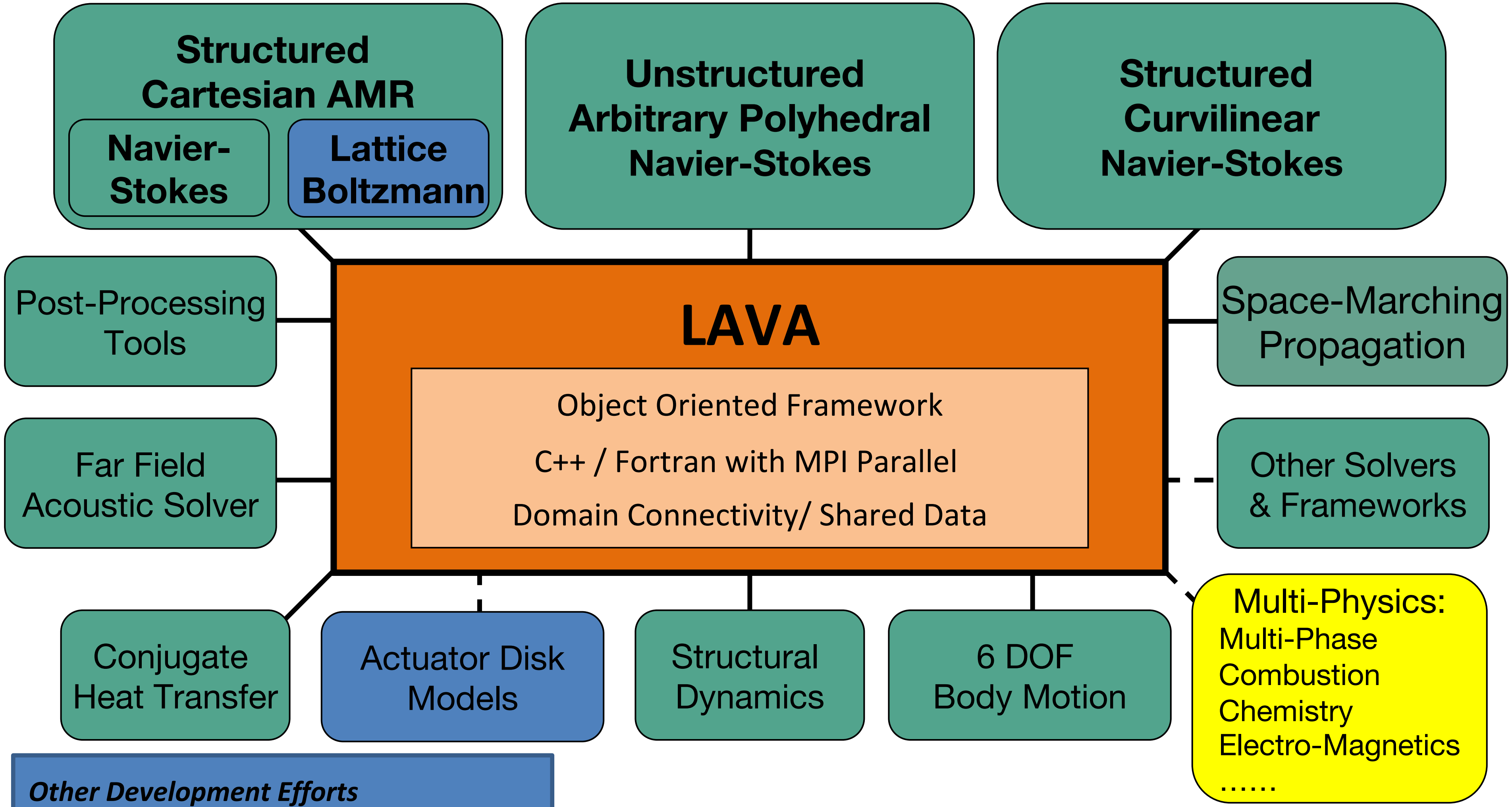


- Essentially no manual grid generation
- Highly efficient structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

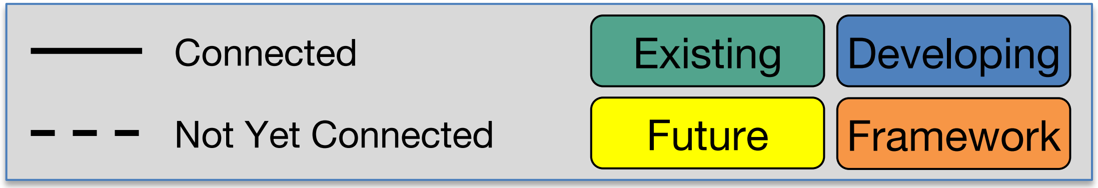
Predict multi-rotor and rotor-fuselage interaction noise, including broadband noise for a quadcopter:

- Simulate complex vehicle without simplification
  - ✓ Automatic mesh generation and immersed boundary representation
- Track all sources of noise as they propagate
  - ✓ Adaptive mesh refinement (AMR) using on-the-fly statistics
- Capture acoustic waves from 135 Hz to 18 kHz
  - ✓ Low-dissipation high-resolution scheme (EMRT) can capture waves accurately with only 5 cells
  - ✓ Near-isotropic cells are best for predicting acoustics
  - ✓ Boundary layers do not play critical role in the quantities of interest for this project
- Short turnaround time for decision making
  - ✓ Automatic grid generation means we can get started immediately
  - ✓ Sub-cycling algorithm increases computational efficiency

Launch, Ascent, and Vehicle Aerodynamics
LAVA Framework



Other Development Efforts
- Higher order and low dissipation
- Curvilinear grid generation
- Wall modeling
- LES/DES/ILES Turbulence
- HEC (optimizations, accelerators, etc)



Kiris at al. AIAA-2014-0070 & AST-2016

Why Lattice-Boltzmann?

10X faster and extremely accurate*

No manual CFD mesh generation

Fast turnaround time

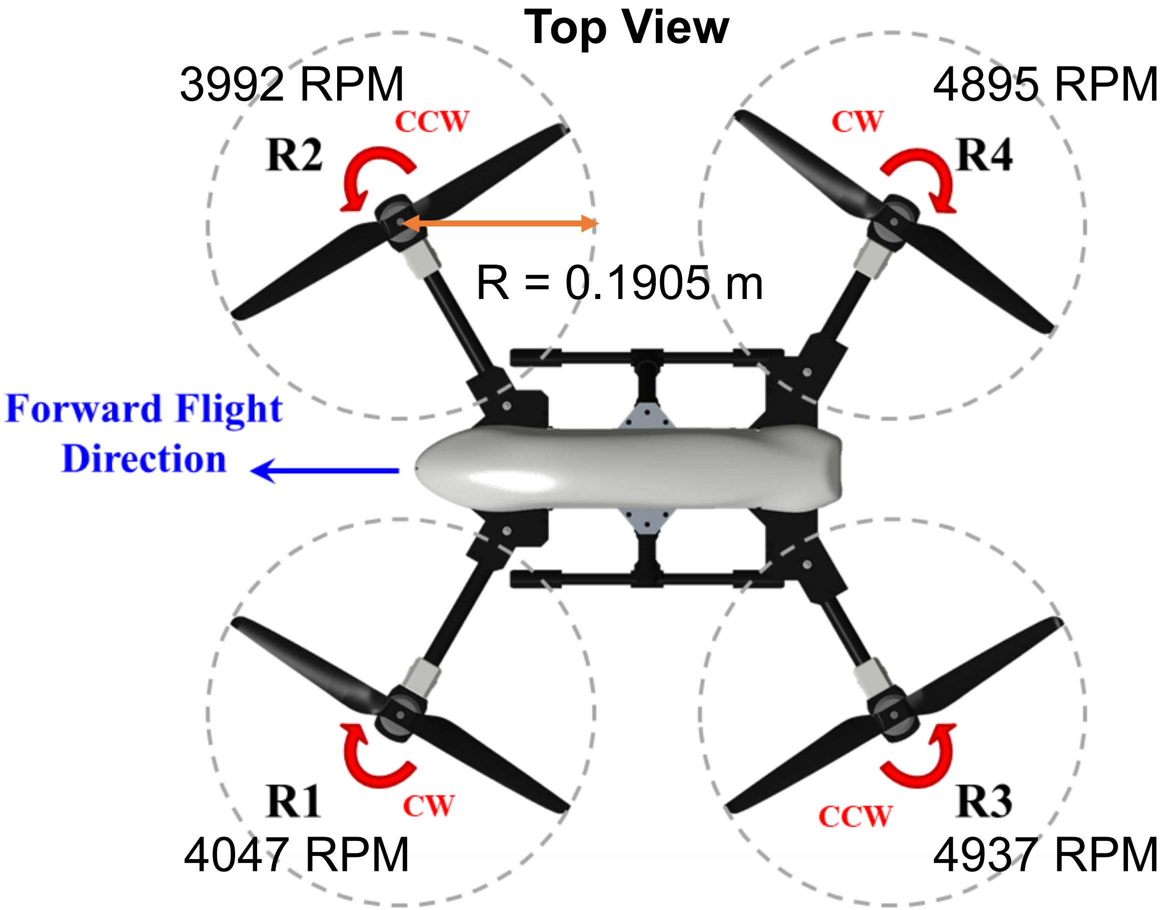
*to perform scale-resolving simulations of low Mach number flows

Objective

- Establish best practices for multi-rotor and vehicle interaction noise predictions, validate predictions, and assess accuracy/resources

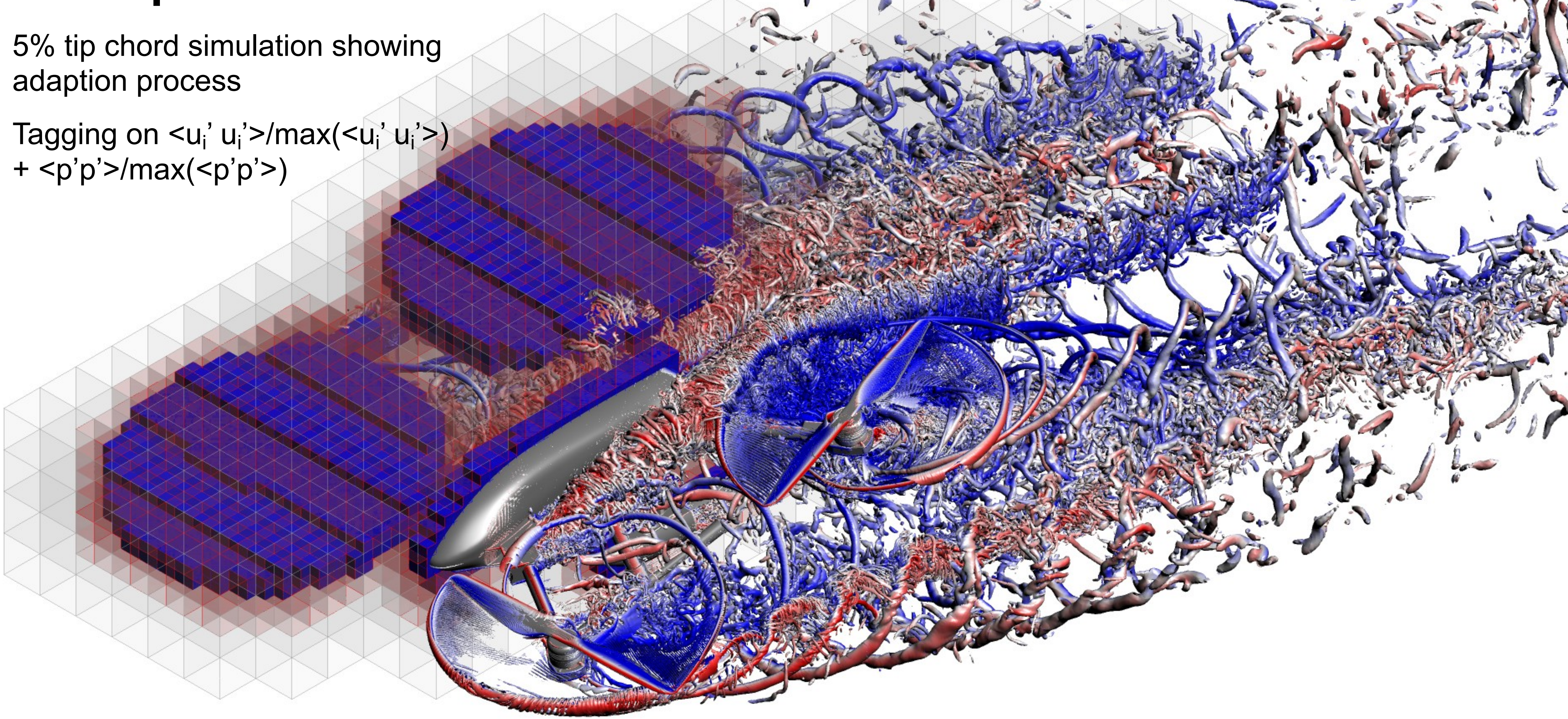
Zawodny, Nikolas, and Nicole Pettingill. "Acoustic wind tunnel measurements of a quadcopter in hover and forward flight conditions." *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*. Vol. 258. No. 7. Institute of Noise Control Engineering, 2018.

Mach = 0.045, AoA = -10°



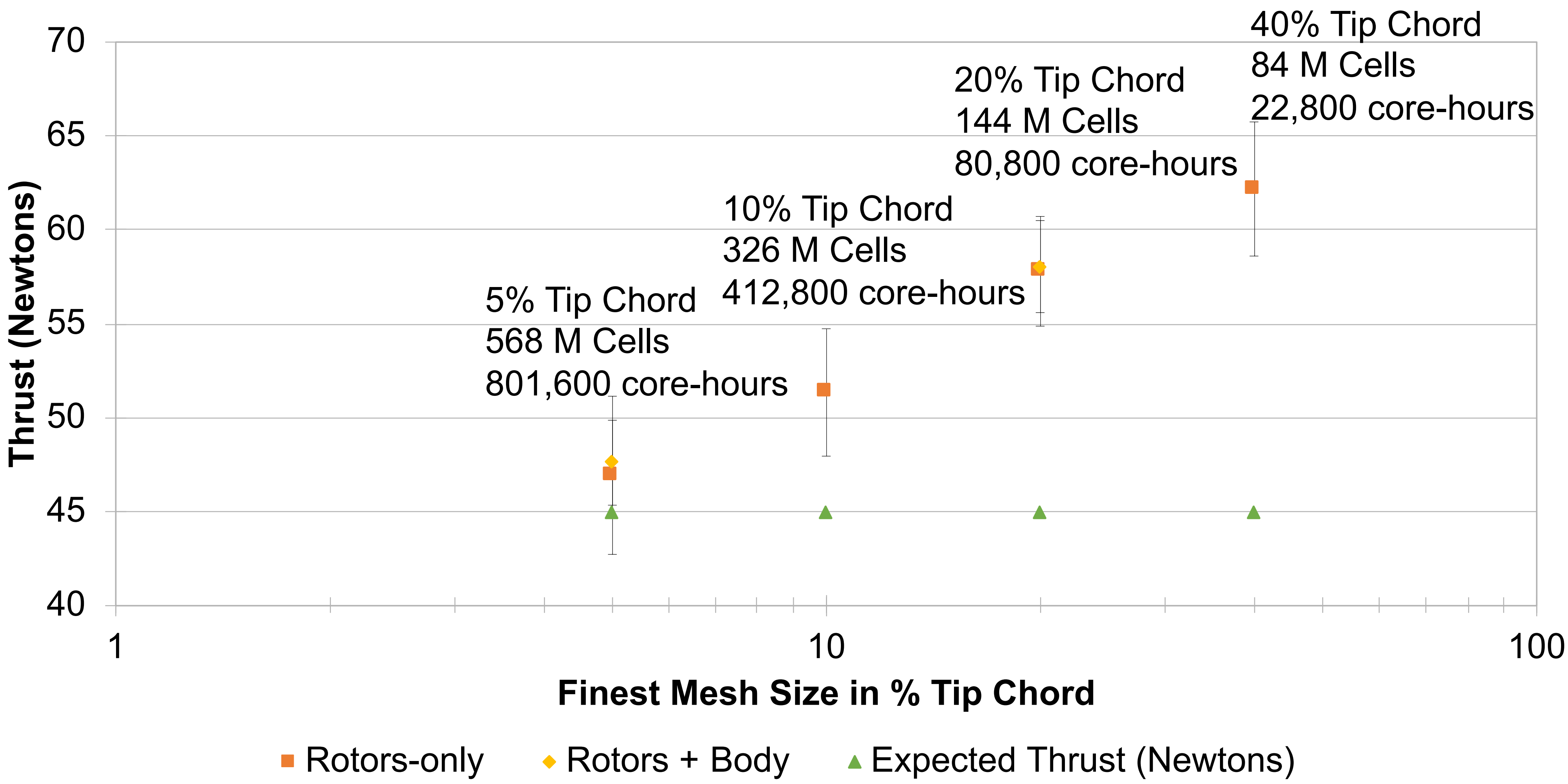
Adaptive Mesh Refinement

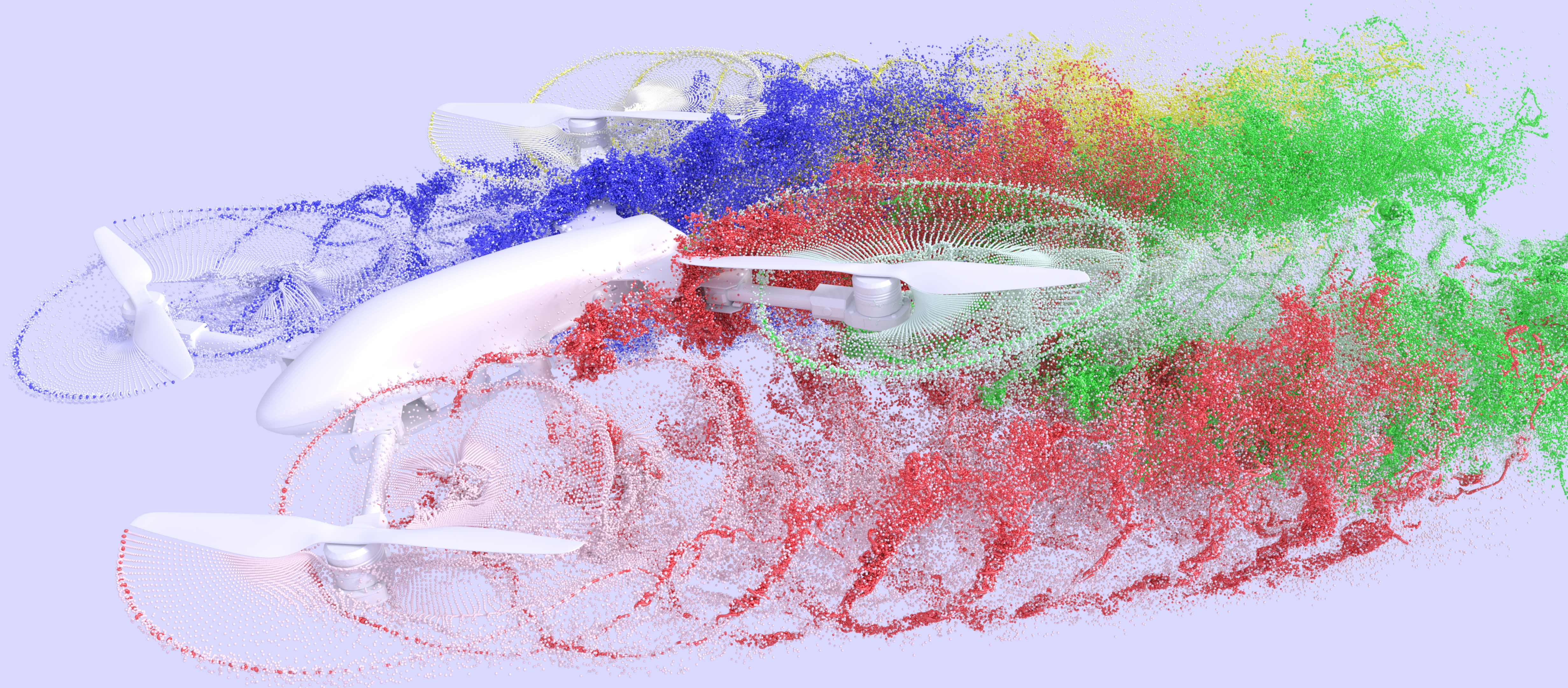
- 5% tip chord simulation showing adaption process
- Tagging on $\langle u_i' u_i' \rangle / \max(\langle u_i' u_i' \rangle) + \langle p' p' \rangle / \max(\langle p' p' \rangle)$



- Left: 3 finest mesh levels box distribution
- Boxes each contain 32^3 cells
- Right: Isosurfaces of Q-Criterion colored by vertical velocity

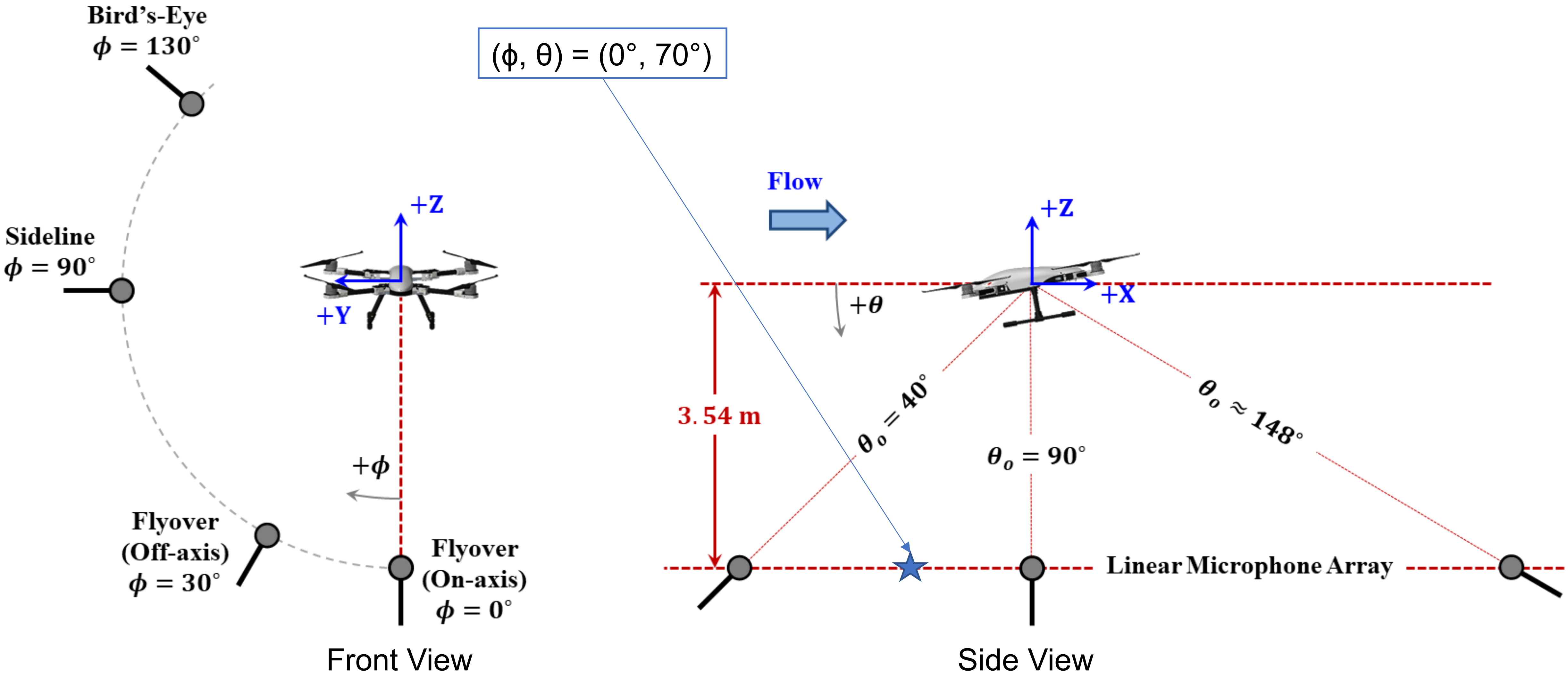
Mesh Convergence of Thrust





Animation Credit: Timothy Sandstrom

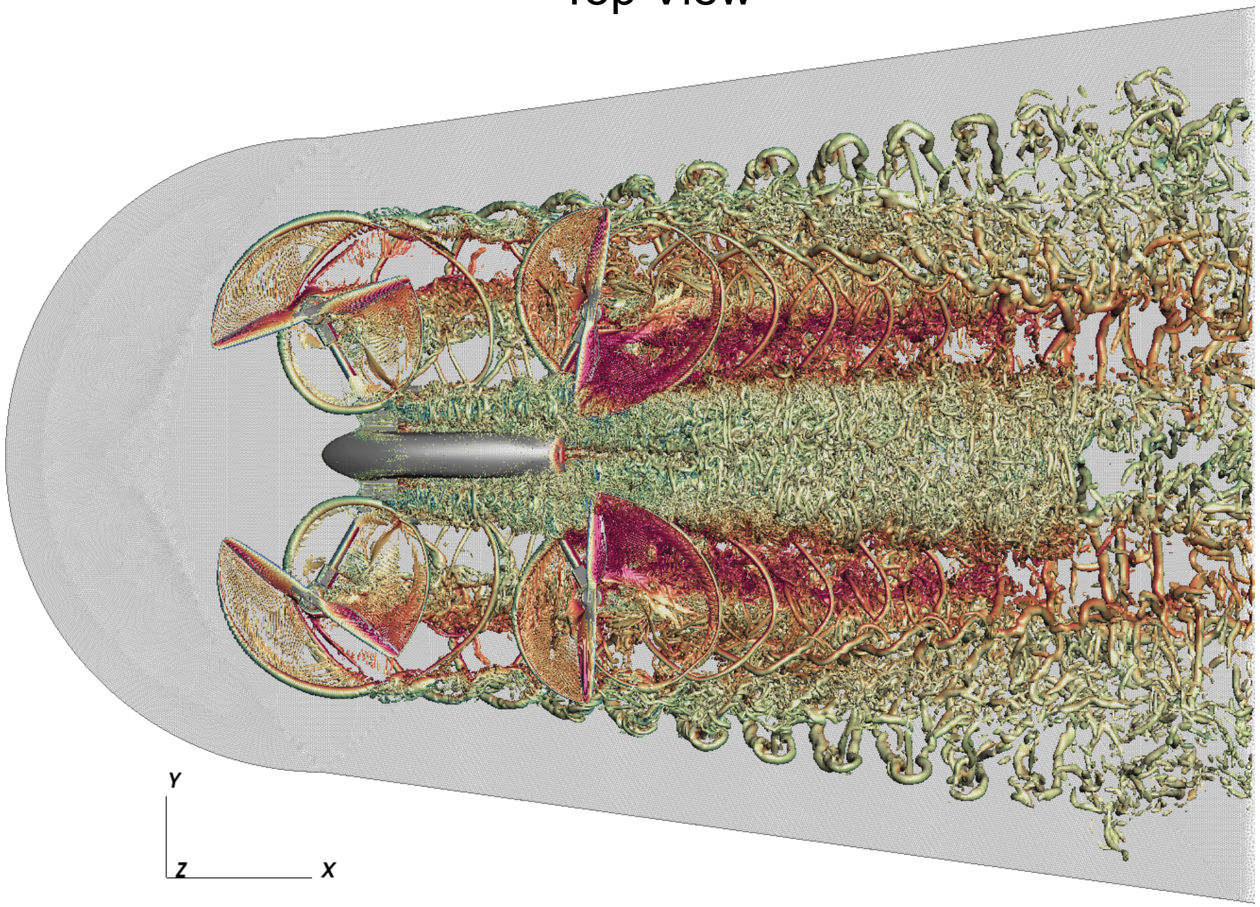
Microphone Location



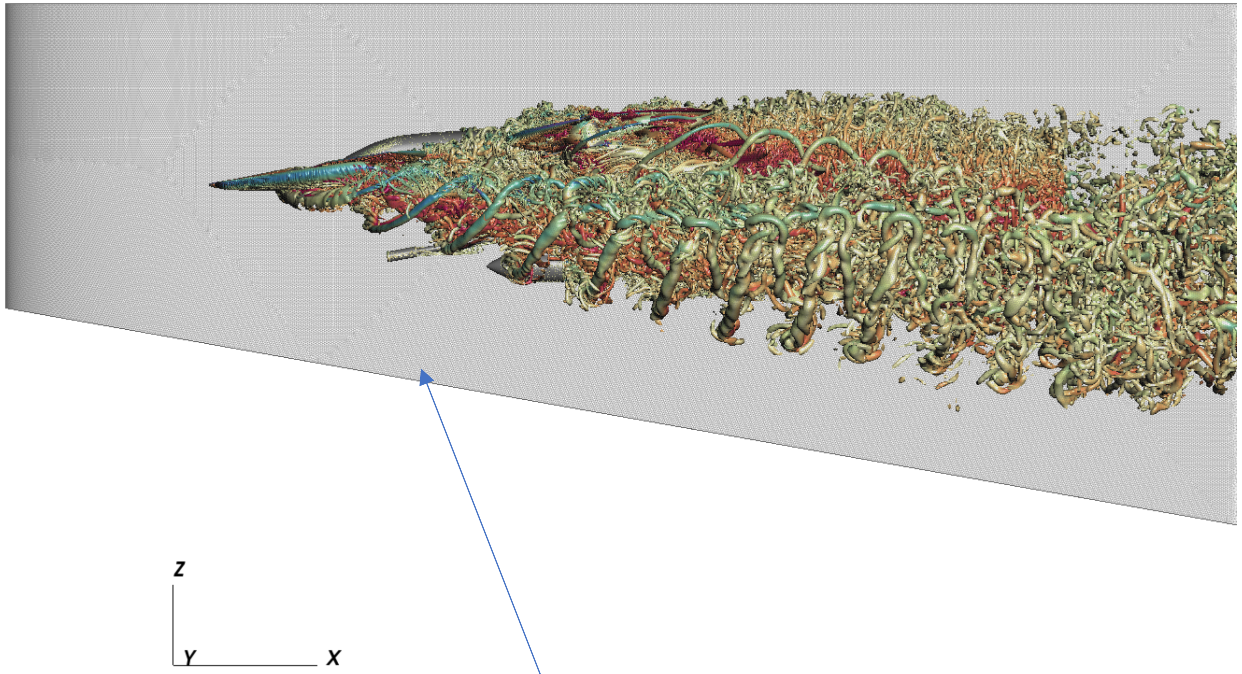
Zawodny, Nikolas, and Nicole Pettingill. "Acoustic wind tunnel measurements of a quadcopter in hover and forward flight conditions." *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*. Vol. 258. No. 7. Institute of Noise Control Engineering, 2018.

Far-Field Noise Propagation with FWH

Top View



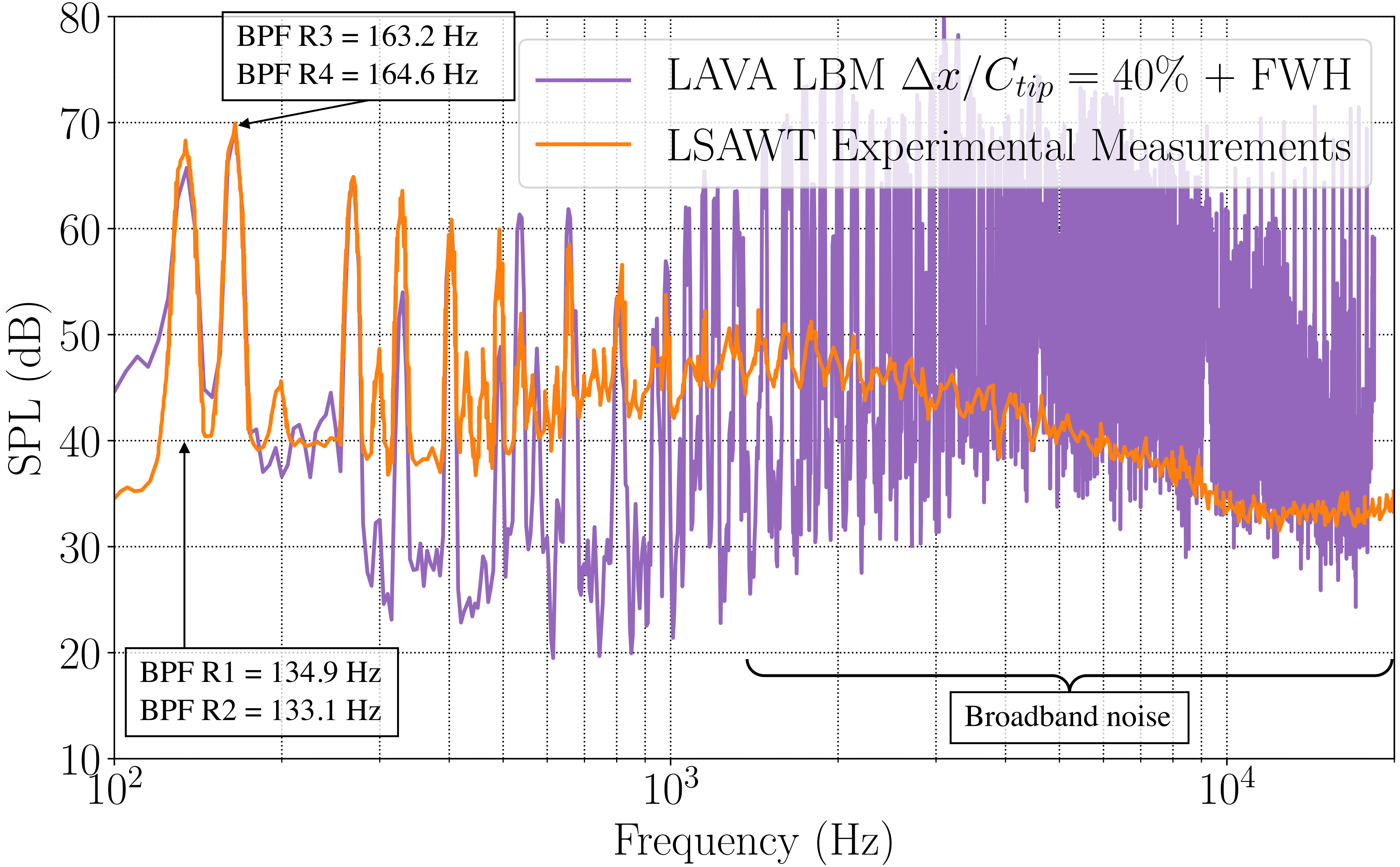
Side View



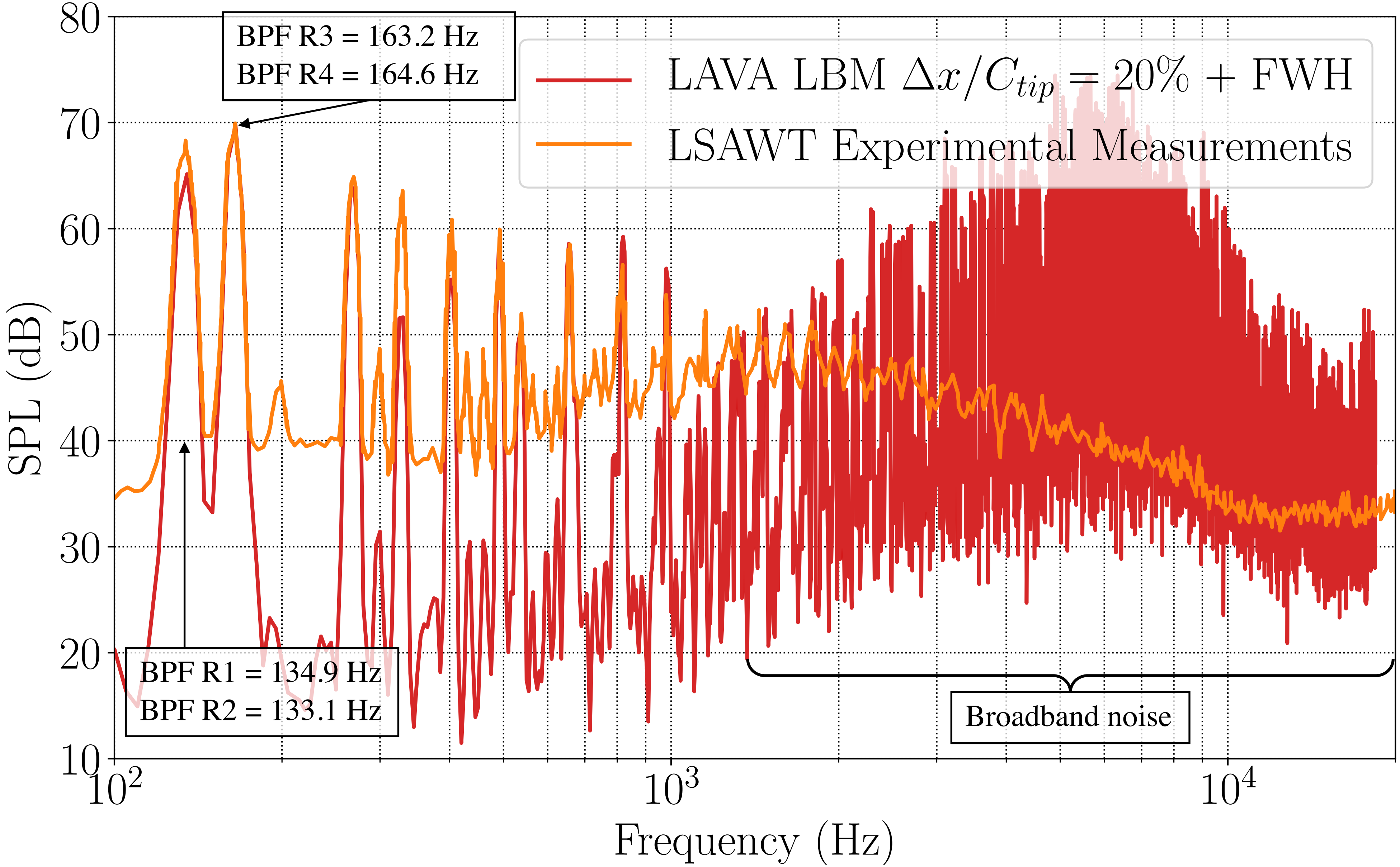
40% tip chord triangle edge length to capture up to 20 kHz

1.37 Million triangles

FWH Narrow-Band Spectra at (ϕ,θ) = (0°,70°)



FWH Narrow-Band Spectra at (ϕ,θ) = (0°,70°)



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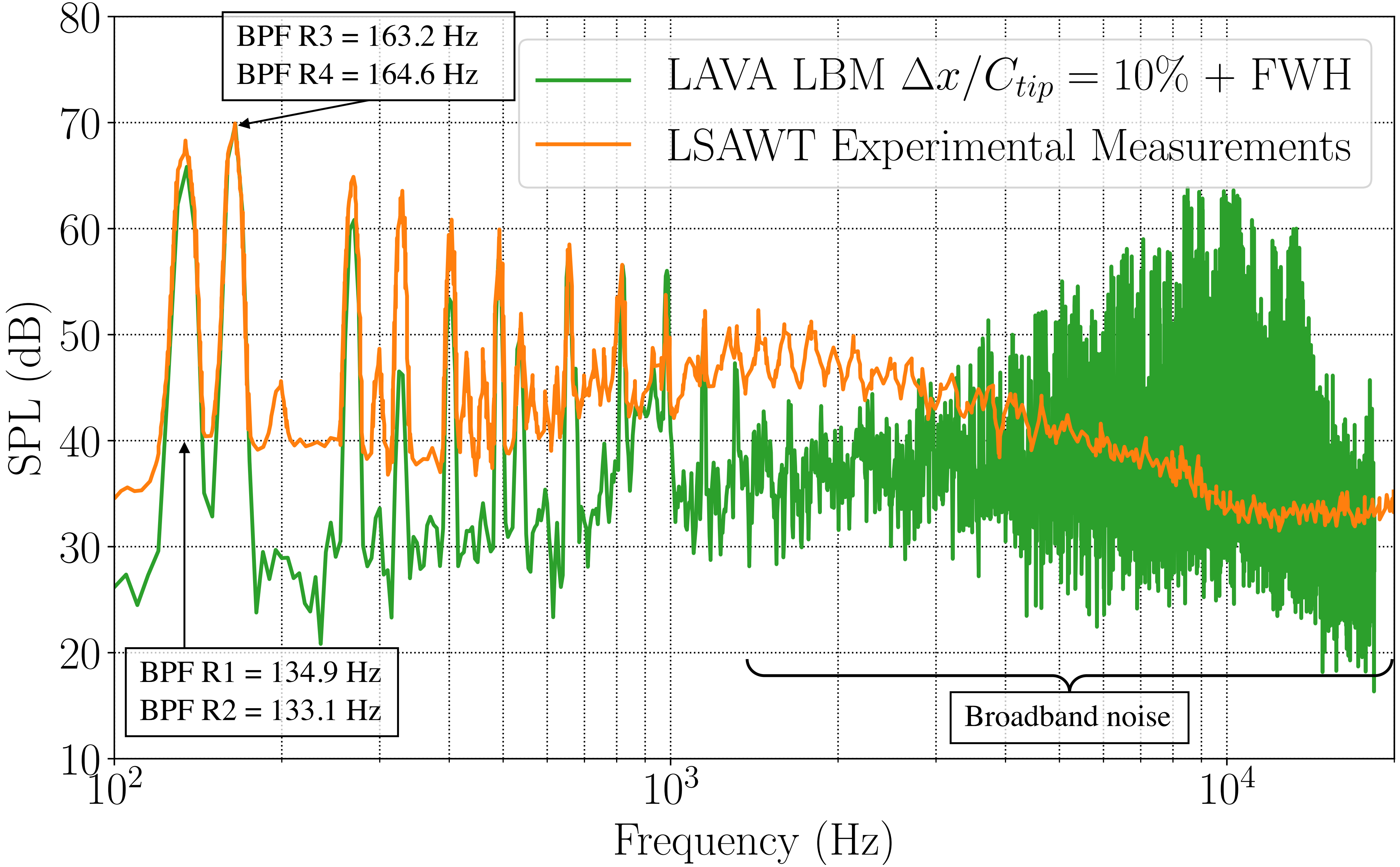

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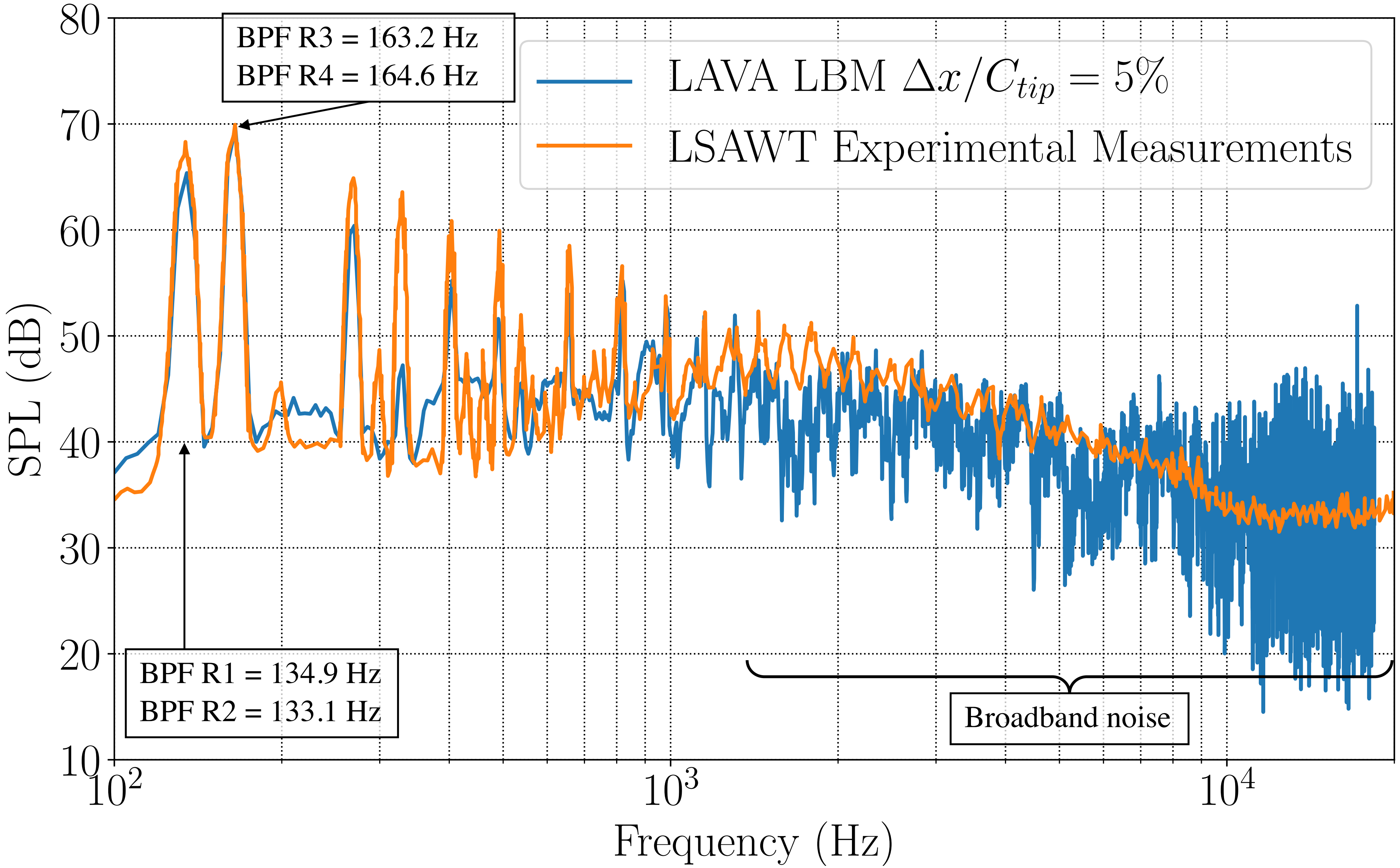
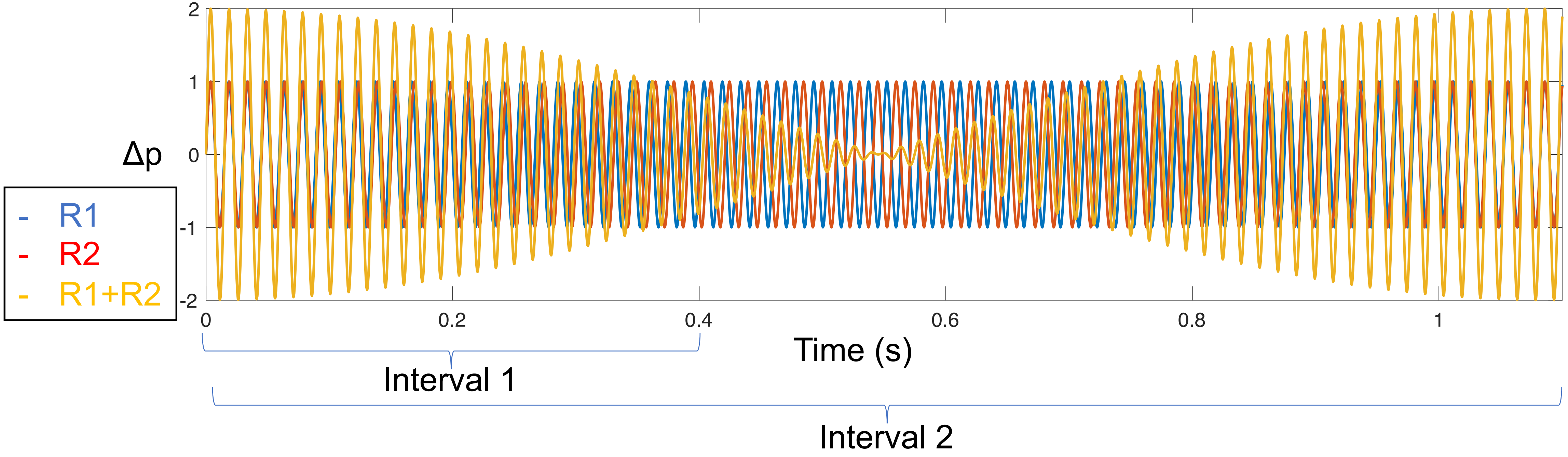


Differences in Acoustic Spectra Between CFD and Experiment

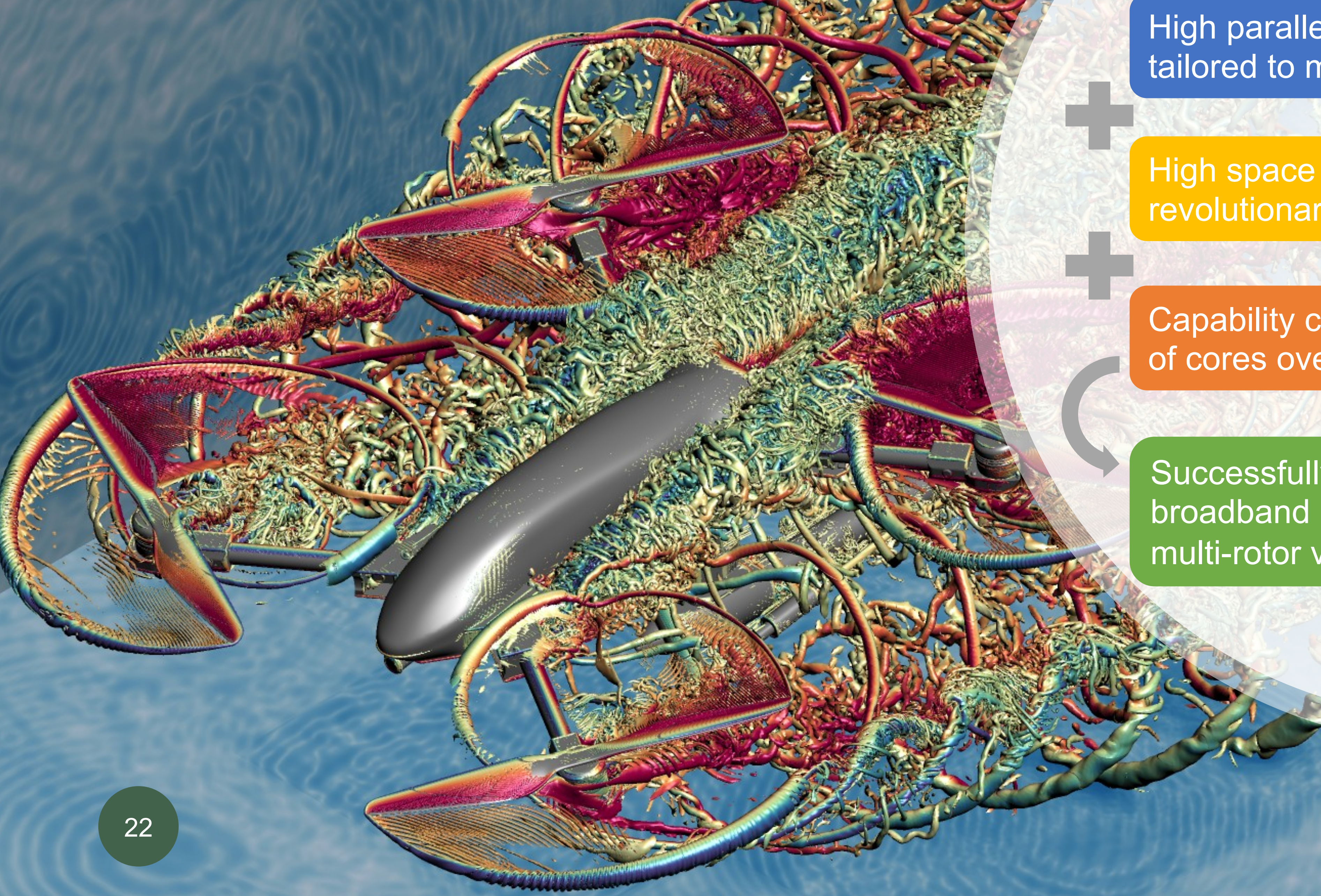
- Beat phenomenon is observed due to slight differences in rotation rate for front rotor pair (period of ~1.1 seconds), and rear rotor pair (period of ~1.4 seconds)



→Spectra from interval 1 will be different than interval 2

→For the same reason we expect differences between spectra from 0.4 seconds interval of CFD to be different from 12 seconds of experimental data

SUI Quadcopter 5% tip chord simulation: isosurfaces of Q-criterion colored by vertical velocity and cut plane colored by logarithm of pressure gradient magnitude



HPC Impact

High parallel efficiency algorithms tailored to many-core architecture

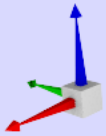
+

High space and time resolution through revolutionary Lattice-Boltzmann Method

+

Capability computing resources (high # of cores over many days)

Successfully predict tonal noise and broadband noise trends of a complex multi-rotor vehicle for the first time



Acknowledgments

- Special thanks to Nikolas Zawodny for a fruitful collaboration, and for providing the quadcopter CAD geometry as tested in the wind tunnel, along with figures describing the experiment, and acoustic data for use in this presentation
- Funding was provided by the Revolutionary Vertical Lift Technologies (RVLT) project, and by the Transformational Tools and Technologies (T^3) project
- Gerrit Stich and Jeffrey Housman for helpful discussions and guidance on FWH far-field noise propagation